Evolution and Depths of the High-Ti Mare Picrite Glass Source Regions

Final Performance Report

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The objectives of this research were to examine the igneous evolution of the Moon with emphasis on the petrogenesis of Mare basalts, lunar troctolites and the Mg-rich suite and on the evolution of the crystallization products of the magma ocean.

I Petrogenesis of mare glasses

Piston cylinder experiments in our laboratory to determine the solubility of ilmenite in mare basalts prove that all mare picrite glasses are significantly undersaturated with respect to ilmenite. The orange picrite glass, for example, contains only about 1/3 the amount of TiO_2 needed to saturate ilmenite at the appropriate liquidus temperatures and pressures. It follows that any ilmenite originally present in the source region was totally consumed during melting, in agreement with the phase equilibria constraints. Indeed, the percent of melting of ilmenite-free source materials must have exceeded by more than a factor of two the percent melting required to produce picrite glasses with 10% or less TiO_2 from ilmenite-bearing cumulates. While some estimates of modal ilmenite originally in the source regions run as high as 10% such high values are unrealistic because they would require 30% or more melting to eliminate ilmenite from the source. Such large degrees of melting are difficult to reconcile with the trace element data (Hughes, et al., 1989). Phase equilibria studies prove that high Ti mare glasses are undersaturated not only with respect to ilmenite but also with respect to high CaO-pyroxene and plagioclase. Indeed I show below that these primitive mare melts were saturated only with olivine and low Ca pyroxene at their source (Hess and Finnila, 1997).

Our experimental results provide the necessary data to approximate the phase diagram to understand the petrogenesis of mare basalt. We take the $MgO-SiO_2-TiO_2$ ternary liquidus at high pressure as the most useful template for our discussions (MacGregor, 1969). This phase diagram has a prominent olivine-enstatite cotectic that is near radial to the TiO_2 apex. Melts generated along this cotectic show an inverse relation between TiO_2 and MgO, as observed in the mare glasses (Delano, 1986). We project our experimental liquids saturated with respect to ilmenite or ilmentite + olivine from $CaAl_2Si_2O_8$ and $CaMgSi_2O_6$ onto the $(MgO-FeO)-SiO_2-TiO_2$ pseudoternary diagram. Theoretical analysis (Hess, 1995) shows that projecting through normative rather than oxide components does least to perturb the correct phase relations.

The compositions of the high TiO_2 mare glasses projected in the same manner all fall on or very near to the olivine-orthopyroxene cotectics between 1.5 and 2.5 GPa (Fig. 1). Certainly, the loci of points lie parallel to the trend of the cotectic. This near coincidence between projected points and phase equilibria is strong evidence that high-TiO_2 picrite melts were extracted from a source having olivine-orthopyroxene in the restite. Indeed, there is no convincing alternative hypothesis. We conclude, therefore, that high Ti mare glasses are near primary liquids derived from an olivine-orthopyroxene source with an average depth of segregation of about 400 km.

Density inversions between very high TiO_2 mare basalt and the lunar mantle which were first predicted by Delano (1990) and confirmed by experiment by Circone and Agee (1996) indicate that such melts become buoyant at depths less than 400 km. Perhaps it is no coincidence that the average depths of multi-saturation and the maximum depths for buoyant rise correspond. Below these depths, Hess (1991) has argued that even negatively buoyant melts can be carried upwards in buoyant plumes if the melts wet only some crystal-crystal boundaries and because sinking melts would crystallize as they descend along their adiabats.

Perhaps a more severe problem is how to preserve the high pressure signature of such melts. In most models, such melts must be isolated, perhaps in large-enough melt pockets, to prevent their equilibration with a shallow mantle. How such isolation is achieved is the focus of future research. See planned work.

II Evolution of the lunar crust and magma ocean cumulates

We have examined the rheological properties of the ancient anorthosite crust during the first 0.5 Ga years using flow laws appropriate to dry plagioclase-rich lithologies.(Hess and Parmentier, 1997). We have concluded from this study that the anorthosite crust achieved sufficient strength very early in its evolution to be capable of supporting more dense gabbroic plutons of Mg* suite or mare basalt parentage. From these observations we have concluded that the apparent vertical crustal layering into anorthosite upper crust and lower mafic crust (e.g. Ryder et al., 1997) was largely determined by underplating of the crust by Mg* suite magmas.

Several important ideas arise from these studies:

1. The development of an early mafic lower crust and the consequent stripping away of the anorthosite upper crust by impact processes, would create multi-ringed basins largely floored by dense mafic crust. This physical setting is ideal for the eruption of dense mare basalts to the lunar surface. Indeed, all but the most high TiO_2 mare picrite melts are less dense than noritic to gabbroic cumulates that characterize the lower crust. The problem of getting dense magmas through less dense anorthosite crust is thereby overcome. The near absence of mare volcanism in the South Polar Aitkin Basin demonstrates that the conditions for the generation of mare volcanism lay deep within the moon and that the physical conditions obtained within the lunar crustal by impact processes were only of secondary importance; the mare source regions were not influenced by the cratering processes associated with the multi-ring basin formation.

2. Having a stronger lower crust (the mafic crust is about 50x stronger than anorthosite) would have the effect of being able to support mascons during an earlier, overall hotter stage of lunar history.

3. And if the lower mafic crust is due to underplating by mafic magmas, it follows that the KREEP layer originally trapped as a sandwich horizon between the anorthosite crust and the mafic cumulates must now exist within the crust, somewhere below the anorthosite layers and above or within the mafic zone.

4. The absence of mare basalt plutons (as revealed by the absence of clasts of mare gabbros in impact breccias) is not due to a weak anorthosite crust especially after about 200 million years since the end of the magma ocean. Even very dense high Ti mare gabbro plutons can be supported within the upper 30km of the crust. Either large volumes of mare basalt volcanism did not precede the excavation of the multi-ringed basins or large plutons of mare basalt rarely formed in the crust.

III Thermal convection in thermally stratified lunar mantle

Our previous model for the internal evolution of the Moon and for the petrogenesis of mare basalts calls for a density stratified cumulate lower mantle that is heated from below (Hess and Parmentier, 1995). Such density stratification is a necessary component of our model because in its absence, plumes would rise directly and promptly to the lunar surface and would explain neither the high pressures inferred for mare basalts (Hess and Finnila, 1997) or the age of emplacement.

Numerical experiments were performed to model the formation of diapiric upwellings in chemically stratified viscous fluids heated from below (Alley et al., 1997). This model predicts the successive formation of multiple conductive thermally boundary layers thereby producing thermally and chemically mixed layers. The mixed layers developed additional unstable boundary layers and in this way propagate the instability upwards in the lunar mantle. An important result of this study is that plumes cannot reach the upper mantle but instead stall and probably release their melts from deep within the lunar mantle. Such models might explain the high pressure petrogenesis of mare picrite glasses and may limit the role of polybaric melting. Perhaps equilibrium melting with a single stage segregation event might be the correct model after all?

IV Mafic anomalies in South Pole-Aitkin basin

Five color images from Clementine show that the dominant rock type identified throughout the SPA is dominated by orthopyroxene rather than either olivine or clinopyroxene (Pieters et al., 1997). This result suggests that the lower mafic crust has been exposed by the SPA impact event. If true, this has important implications for the crustal stratigraphy as well as the physics of the impact. The impact, for example, might have been at a very low angle. The absence of cryptomare - no high CaO-pyroxene - is consistent with the overturn model which places the mare source region deep within the moon. In comparison a shallow source would have undergone melting and mare basalts should have readily filled the basin. Further studies are vital to placing constraints on the evolution of the lunar crust and mantle.

V Melting kinetics and constraints of chondrule formation

We completed our experiment and theoretical investigation on congruent melting kinetics and used the results to place constraints on the duration and maximum temperatures experienced by the interiors of relict-bearing condrules (Greenwood and Hess, 1996). Specifically, chondrules containing relict forsterite or enstatite cannot have been heated above their respective melting temperatures (1901°C, ~1577°C) for more than a few seconds. We have shown than the normal growth model and the physics of surface dominated melting processes are good representation of the melting kinetics of silicate and oxide phases subjected to moderate amounts of superheat (Greenwood and Hess, submitted). We believe that such models are critical to our understanding of melting processes in a nebular environment.

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